A NEW LASER MICROMACHINING TECHNIQUE USING A MIXED-MODE ABLATION APPROACH

Xiaoshan Zhu, Jin-Woo Choi, Robert Cole, and Chong H. Ahn

MicroSystems and BioMEMS Lab
Department of Electrical and Computer Engineering and Computer Science
University of Cincinnati
Cincinnati, OH 45221-0030, USA

ABSTRACT

This paper presents a novel laser micromachining technique using a mixed-mode ablation approach. Some important techniques, which include laser drilling, laser ablation, and laser cutting, have been developed to overcome common problems in laser micromachining, such as material recast, big heat affected zone (HAZ) problem, and laser polarization effect. Ablation parameters for various microstructures on single crystalline silicon have been optimized to demonstrate through-holes, post microstructures, and gear structures. The developed laser micromachining technique has minimized common problems in laser micromachining – HAZ, recast, microcracks to the sidewall of structures, and laser polarization effect.

INTRODUCTION

Recently laser micromachining has become a standard industry technique in MEMS applications due to its high process flexibility, for instance, direct patterning on various materials – hard materials (diamond, glass, silicon, metal, and ceramic) and soft materials (polymer and plastic). Therefore, there has been an increasing application potential in laser micromachining for a microanalytical system [1], high fidelity structures in laser-LIGA [2], three-dimensional optical surface [3], and as a method to remove polymer residue after SU-8 processing [4].

In spite of the increasing applications, the principle of laser ablation for many materials is still under investigation and no accurate mathematic model is available to describe it [5]. A laser ablation sequence is generally considered to be following steps: photon absorption by material; electronic excitation or thermal process; rapid heating; and then explosive expansion of materials. Usually a nozzle is used to blow gas through surface to remove the evaporated materials. However, one of major problems in laser ablation is that evaporated materials are re-solidified in nearby space and deposited on the surface to form recast. Other major problems include HAZ (heat affected zone) due to heat diffusion into the surrounding material, stress wave generated because of different temperature distribution in the material, and material plume generated in ablation. HAZ and stress wave make it difficult to achieve small feature size and cause microcracks on microstructures or surrounding area. Material plume decreases the ablation rate by absorbing the energy of laser and makes it difficult to do deep ablation.

For these reasons, there has been a lot of reports on improving laser micromachining using techniques such as ultrasonic cleaning to remove debris inside microstructures [6], a specially developed anti-spatter composite coating (ASCC) to decrease recast on the material surface [7], and a diffractive optical element (DOE) to overcome laser polarization [8]. Ultrasonic cleaning, however, could destroy the structure easily and was just used for Teflon, ASCC was specified to metal alloy, and DOE makes the optical system complicated and expensive.

In this paper, we have introduced and developed a novel mixed-mode laser micromachining technique to fabricate deep 3-dimensional microstructures on silicon, glass, and plastic substrates. Several important techniques such as laser drilling, laser cutting, and laser ablation have been developed to overcome the common problems in laser micromachining, such as the material recast, the large heat affected zone (HAZ), and the laser polarization effect. Based on the developed laser micromachining techniques, various through-holes and microstructures on silicon, glass or plastic have been fabricated.

LASER MICROMACHINING SYSTEM SET-UP

The laser micromachining system (LMT 4500, Potomac Photonics Inc., MD) used for this work is illustrated in Figure 1, which mainly includes an excimer laser, an optical delivery system, and an NC (Numerical Code) stage.

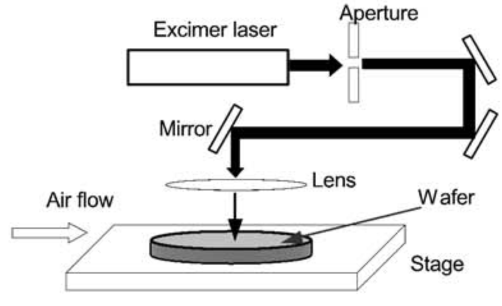


Figure 1. *Schematic illustration of laser micromachining system.*

The laser used in the system is a KrF excimer laser (Model PL-1500, 248 nm) with 10 ns pulse duration and 10 mJ pulse energy. The optical delivery system consists of an adjustable square aperture unit, three high-reflectivity dielectric beam steering mirrors, and a fixed focal length lens. A pulsed laser beam passes through the adjustable square aperture, and then is reflected by three steering mirrors, and finally focused by a lens. The focused spot sizes are available from 2 μm to 250 μm. The NC stage contains a *xy*-motion-axis stage, which allows target translation in two-dimensional directions, and a *z*-axis stage, which translates the focusing lens for adjustment of the laser and video focal plane. A central computer is used to control laser and NC stage.

MIXED-MODE ABLATION TECHNIQUE

The laser micromachining system has two operation modes – pulse synchronization output (PSO) mode and freerun mode. Under PSO mode, the stage movement triggers the laser firing so that any pattern can be ablated on wafer. Under the freerun mode, laser firing is triggered by the user after power and repeat rate are initialized, so that free ablation can be run as illustrated in Figure 2.

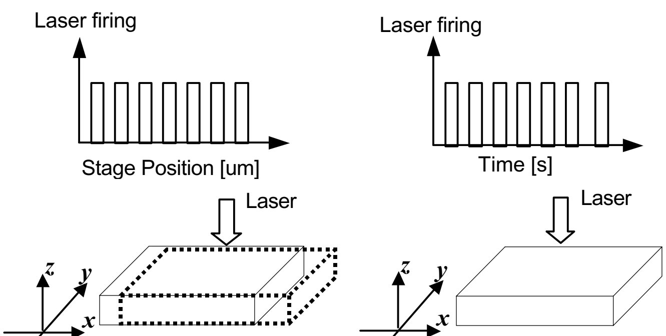


Figure 2. *Standard direct ablation methods: (a) Stage motion triggers laser firing in pulse synchronization output (PSO) mode and (b) user interface fires laser in freerun mode.*

A major problem with the PSO mode ablation is the heat absorption by sidewall of microstructure. In the freerun mode, HAZ and laser polarization effect will be dominant. The newly developed laser drilling combines the two operation modes together. It consists of three steps as described in Figure 3: (1) The outline of the desired hole shape is traced using the PSO mode with a small beam size and low energy. This prevents damage to the wafer surface. (2) The central portion of the holes is removed using freerun mode in order to accelerate ablation and to decrease laser energy absorption by sidewall. (3) The PSO mode is used again to maintain the round shape. These steps are repeated in an iterative fashion to drill through the entire thickness of the wafer and the second step is especially useful in thick material ablation.

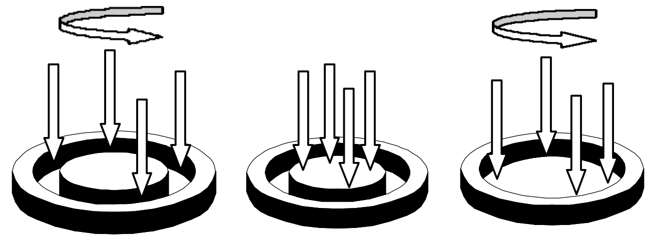


Figure 3. *A new mixed-mode laser ablation technique for drilling through-holes: (a) initial patterning in PSO mode to prevent surface damage; (b) drilling in freerun mode to avoid laser absorption by side-walls; and (c) finishing in PSO mode to achieve vertical side-walls.*

The optimization of ablation parameters is very important in the mixed-mode ablation. In this work, we have focused on single crystalline silicon, Pyrex glass, and plastic substrates. Table 1 lists important parameters in PSO and freerun modes for these materials. The mixed-mode laser ablation not only decreases the surface damage, recast, energy absorption by sidewall, laser polarization effect, and HAZ, but also makes parameter optimization flexible for any ablation pattern. Under only PSO mode or freerun mode, it is rather difficult to use the same ablation parameters to drill a small through-hole (i.e. less than 100 μm diameter on 300 μm thick silicon wafer) and cut a big through rectangle (i.e. 1 cm x 1 cm) at the same time. However, the newly developed mixed-mode ablation makes the ablation parameters changeable from mode to mode.

Table 1. *Processing parameters and their typical values for PSO mode and freerun mode.*

PSO mode	
Power (mJ/pulse)	0.02~0.35
Stage feed rate (program steps/ms)	0.06~0.1
Laser focused spot size (μm)	20~35
Trigger distance of stage motion (μm)	1~5
Freerun mode	
Power (mJ/pulse)	0.03~0.2
Laser focused spot size (μm)	20~35
Repeat rate (Hz)	1~200

RESULTS

Single crystalline silicon (280 μm-thick), Pyrex glass (500 μm-thick), and plastic substrate (1.5 mm-thick PMMA and olefin copolymers) were investigated in experiments. Debris deposited around microstructures after ablation was chemically removed by cleaning in diluted HF solution (0.5%) for silicon or in acetone for plastic substrate.

Optimization of ablation parameters for silicon in PSO mode is mainly based on the ablation rate as a function of stage feed rate as shown in Figure 4. The laser energy fluence is fixed at 36.4 J/cm^2 and 19.2 J/cm^2 respectively. Figure 4 shows that a peak is observed between ablation depth and stage feed rate. In low traverse speed of stage, energy is mainly absorbed in lateral direction. The ablation channel has shallow depth but relatively big width. As the stage traverse speed (feed rate) increases, HAZ decreases and ablation depth goes up. As feed rate increases further, laser ablates a discontinuous track because the laser cannot be triggered fast enough. So ablation depth decreases and the ablated channel's edge becomes rough. Beyond a certain stage feedrate, the synchronization between the stage and the laser is lost so that no energy is delivered.

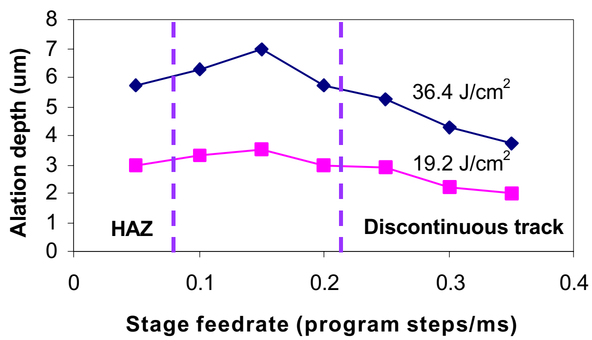


Figure 4. *Average ablation depth as a function of stage feed rate for different laser energy fluence.*

Optimization of ablation parameters for silicon in freerun mode is mainly based on the ablation rate as a function of ablation time (also ablation shot numbers). Figure 5 shows the relationship between the ablation time and the average ablation depth for silicon under different energy fluence. Almost linear relationship between the average ablation depth and the ablation time (also the ablation shot numbers) can be observed. But when ablation depth goes up, plume introduced in the ablation will absorb more and more laser energy so that ablation rate will decrease.

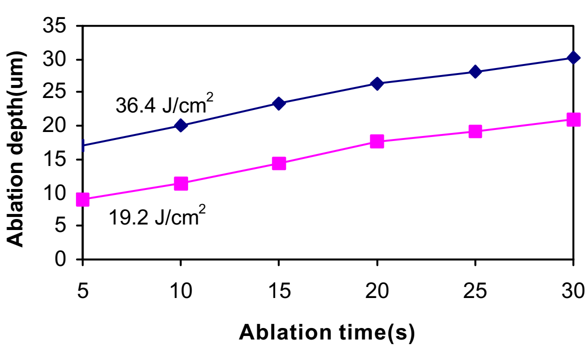
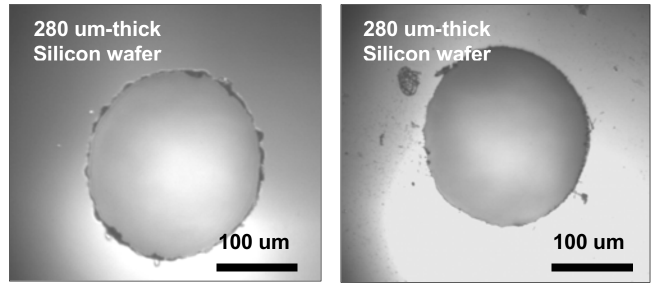


Figure 5. *Average ablation depth as a function of ablation time while maintaining the repeat rate at 200 Hz.*

Figure 6 shows a laser drilled through-hole on a 280 µm-thick silicon wafer by mixed-mode ablation method. No heat absorption/polarization problems have been observed and sidewall angle is larger than 88.2^o, achieving almost vertical sidewall. Table 2 summarizes the optimized ablation parameters in PSO mode and freerun mode.



(a) (b)

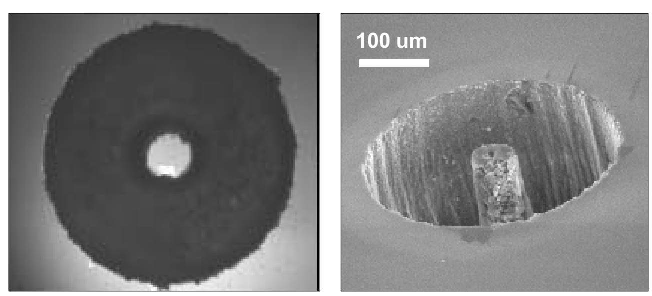
Figure 6. *Microphotographs of process results using the developed mixed-mode laser micromachining technique: (a) entrance of through-hole and (b) exit of through-hole. Side-wall angle is larger than 88.2^o. No heat absorption/ polarization problems have been observed.*

Table 2. *Mixed-mode ablation parameters for through-hole drilling on single crystalline silicon wafer.*

PSO	Fluence	Beam size	Feed rate	Trigger distance
Step1	6.37 J/cm^2	18 µm	0.05	1 µm
Step3	16.2 J/cm^2	20 µm	0.1	1 µm

Freerun	Fluence	Beam size	Rep rate
Step2	16.2 J/cm^2	20 µm	40~70 Hz

Other microstructures have also been fabricated using the developed laser micromachining technique as shown in Figures 7 and 8.

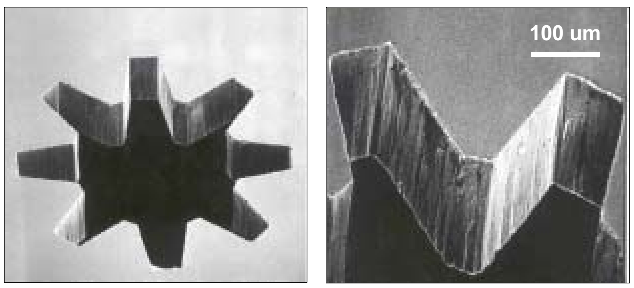


(a) (b)

Figure 7. *SEM microphotographs of a post structure on silicon wafer fabricated using the developed mixed-mode laser micromachining technique. Diameter of the post structure is approximately 50 µm.*

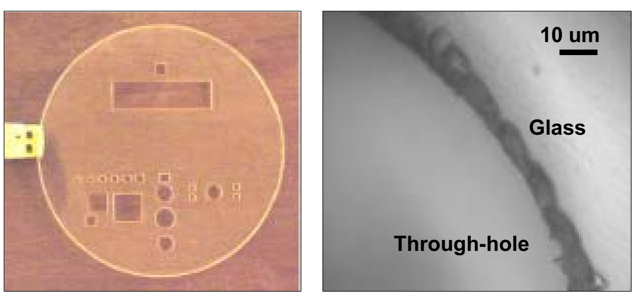
Mixed-mode ablation approach is also suitable for soft materials such as PMMA or olefin copolymers. Similar parameter optimization has been performed for 1.5 mm-thick olefin copolymers. Figure 9 (a) demonstrates various micropatterns patterned on 2-inch olefin-copolymers substrate using the developed mixed-mode ablation method. As shown in the photograph, there are many small through-holes and large through-rectangles or squares. Figure 9 (b) shows the edge of the through-hole structure on a 500 μm-thick Pyrex glass wafer with no noticeable microcracks and heat affected zone.

The alternative operation modes in mixed-mode ablation make the ablation parameters changeable from mode to mode so that both small complicated structures and big patterns can be ablated in one laser process.



(a) (b)

Figure 8. *SEM microphotographs of a gear structure on silicon wafer showing vertical sidewalls.*



(a) (b)

Figure 9. *Laser-micromachined patterns: (a) on a 1.5 mm-thick 2-inch-diameter plastic wafer (olefin-copolymers) and (b) on a 500 μm-thick Pyrex glass wafer using the mixed-mode ablation approach.*

CONCLUSIONS

The novel mixed-mode laser micromachining technique, using LMT 4500 (Potomac Photonics Inc., MD) laser system, has been developed and successfully demonstrated for drilling, ablation, or cutting in this work. Using the developed laser ablation technique, we optimized ablation parameters for various microstructures on single crystalline silicon such as through-holes, post structures, and gear structures. We have also optimized ablation parameters for plastic substrate (olefin-copolymers and PMMA) and demonstrated the ability of arbitrary pattern ablation by simultaneously drilling small holes and cutting big through rectangles on a 1.5 mm-thick plastic substrate. The developed laser micromachining technique has shown promising results – minimized HAZ, minimized recast, no noticeable cracks to the sidewall of structures, and minimized polarization effect. Moreover, this technique shows that both small complicated structures and large patterns can be ablated in one laser process. It makes the ablation process very flexible. The novel mixed-mode ablation technique has great potential in overcoming common problems in laser micromachining as a flexible and versatile tool for MEMS applications.

ACKNOWLEDGEMENTS

This research was fully supported by a DARPA grant under contract AF F30602-00-1-0569 from *BioFlips Program*, MTO/DoD, USA. The authors gratefully acknowledge Mr. Chris Selley at Potomac and Mr. Jeff Simkins at the University of Cincinnati for technical discussions. The authors also thank Mr. Ramachandran Trichur at the University of Cincinnati for SEM analysis.

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